1. Name of Experiment/Project/Collaboration: *ICARUS*
2. Physics Goals
    a. Primary : *Search for sterile neutrinos at the eV mass scale through both appearance and disappearance channels at FNAL Booster Neutrino Beam exploiting three LAr-TPC detectors at different distances from the proton target: LAr1-ND at 110 m, MicroBooNE at 470 m and ICARUS-T600 at 600 m.*
    b. Secondary: *Precision neutrino -argon cross sections with about a million of interactions in the few hundreds MeV to few GeV energy range in the Booster Neutrino Beam and with the* νe *enriched off-axis Numi beam.*
3. Expected location of the experiment/project: *Fermilab*.
4. Neutrino source: *Booster Neutrino Beam (BNB) and NuMi beam*.
5. Primary detector technology: *LAr-TPC*
6. Short description of the detector: *The ICARUS-T600 is the biggest LAr-TPC detector ever realized after many years of R&D studies with prototypes of growing mass developed both in laboratory and with industry involvement. The ICARUS-T600 was operated for three years at the LNGS underground laboratory collecting about 3000 neutrino interactions with the CNGS neutrino beam. Nowadays, it represents the state of the art of this technique and it marks a major milestone in the practical realization of large-scale LAr detectors. The ICARUS T600 detector consists of a large cryostat split into two identical, adjacent modules filled with about 760 tons of ultra-pure liquid Argon, ~ 476 t active mass. Each module houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode. A uniform electric field (E_{drift} = 500 V/cm) drifts ionization electrons towards the anode, consisting in three wire arrays that guarantee a stereoscopic event reconstruction. A total of 53248 wires are deployed, with a 3 mm pitch, oriented on each plane at a different angle (0°, +60°, -60°) with respect to the horizontal direction. A remarkable resolution of about 1 mm^3 is uniformly achieved over the whole detector active volume. The detector will be equipped with a new internal light collection system for the detection of the scintillation light. After the ongoing overhauling phase at CERN the detector will be transferred at Fermilab to be installed at shallow depth at 600 m from the target along the Booster Neutrino Beam line.*

    The detector operation on surface represents a new problem compared to the underground operation at LNGS since several uncorrelated cosmic rays will occur in T600 during the 1 ms drift window readout at each triggering event. About 12 muon tracks per drift in each ICARUS half module were measured on surface during the Pavia 2011 run. In order to reconstruct the true position of each track, it is necessary to associate precisely the related timing of each element of the TPC image with respect to the trigger time. Moreover photons associated with cosmic μ represent a serious background for the ν_e appearance search, since electrons generated in LAr via Compton scattering / pair production can mimic a ν_eCC signal. In order to strongly mitigate the cosmogenic background, all the c-ray particles entering the detector must be unambiguously identified. This can be achieved by implementing a Cosmic Rays Tagging around the LAr active volume that provides an external timing of each track to be combined with the TPC reconstructed image. This system could consist either of external RPCs or scintillators or internal readout plates detecting ionization signals. For instance the adoption of a full coverage muon tagging system with 95% detection efficiency of single muon hit could ensure 99% efficiency in c-rays identification in T600, relying on double crossing of muons (only 15% are expected to stop in LAr).

7. List key publications and/or archive entries describing the project/experiment.
    - *C. Rubbia, CERN-EP/77-08, 1977.*
    - *S. Amerio et al., (ICARUS Collaboration), Nucl. Instr. And Meth. A527 (2004) 329.*
    - *F. Arneodo et al., (ICARUS Collaboration), Phys. Rev. D74 (2006) 112001.*
    - *C. Rubbia et al., (ICARUS Collaboration), JINST 6 (2011) P07011.*
    - *M. Antonello et al., (ICARUS Collaboration), EPJ C73 (2013) 2345.*
    - *M. Antonello et al., (ICARUS Collaboration), EPJ C73 (2013) 2599.*
    - *M. Antonello et al., (ICARUS Collaboration), "ICARUS at FNAL", (2014), FERMILAB-PROPOSAL-1052.*
    - *M. Antonello et al., (ICARUS Collaboration), JINST 9, P12006 (2014)*
    - *M. Antonello et al., (ICARUS--WA104, LAr1--ND, and MicroBooNE Collaborations), "A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Booster Neutrino Beam", (2015) http://sbn-docdb.fnal.gov/cgi-bin/ShowDocument?docid=269* .
8. Collaboration
    a. Institution list

CERN, Geneve, Switzerland

Department of Physics, Catania University and INFN, Catania, Italy

Department of Physics, Pavia University and INFN, Pavia, Italy

Department of Physics and Astronomy, Padova University and INFN, Padova, Italy

GSSI, Gran Sasso Science Institute, L'Aquila, Italy

Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Science, Kraków, Poland

INFN LNF, Frascati (Roma), Italy I

NFN LNGS, Assergi (AQ), Italy I

NFN Milano Bicocca, Milano, Italy

INFN Milano, Milano, Italy

INFN Napoli, Napoli, Italy

Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Institute for Radioelectronics, Warsaw University of Technology, Warsaw, Poland

Institute of Physics, University of Silesia, Katowice, Poland

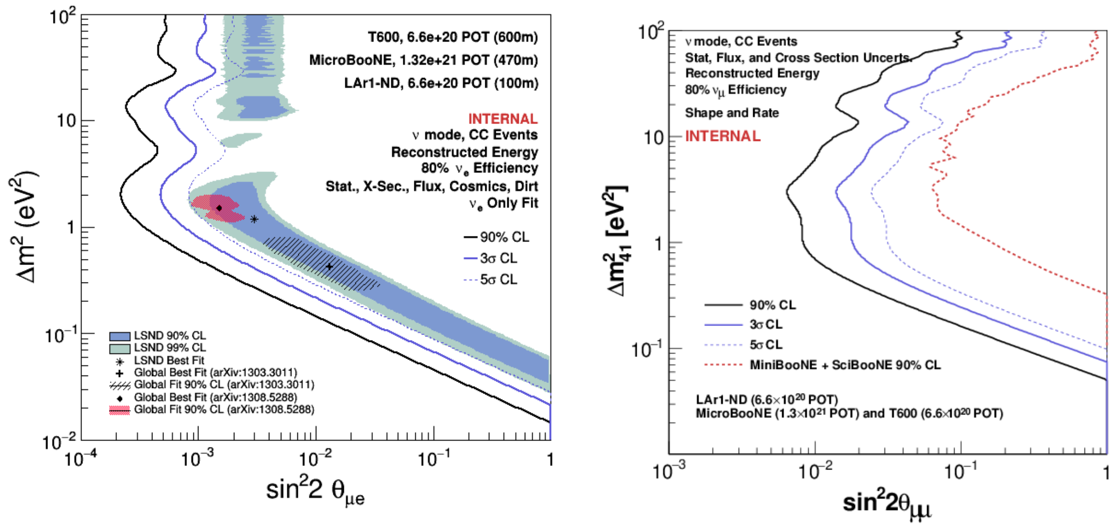
Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland

National Centre for Nuclear Research, Warsaw, Poland

b. Number of present collaborators: *56.*
c. Number of collaborators needed.

9. R&D
    a. List the topics that will be investigated and that have been completed: *The ICARUS-T600 is an existing detector that operated for three years underground in the LNGS laboratory. It is presently being overhauled at CERN. The TPC chambers equipped with a new central cathode will be housed into new aluminum cryostats, actively cooled by boiling nitrogen, surrounded by a passive insulation. An improved light collection system and electronic read-out will be implemented in the detector. No major R&D program is required. Moreover a cosmic muon tagging system surrounding the detector has to be prepared and installed.*
    b. Which of these are crucial to the experiment: *All the new adopted solutions are intended as improvements to the existing fully operational T600 detector that took data with the CNGS neutrino beam.*
    c. Time line: *by 2017*
    d. Benefit to future projects*: The ICARUS-T600 detector, which represents the state of the art of LAr-TPC technique, is directly on the development path to future LBNF Long Baseline Neutrino Facility project.*

10. Primary physics goal expected results/sensitivity: *The proposed SBN experiment will investigate the presence of sterile neutrinos as hinted by neutrino anomalies observed at accelerator neutrino beams, nuclear reactors and radioactive Mega sources in solar neutrino experiments. In three years of data taking the experiment will explore the* ν_μ *to* ν_e *appearance signal with 5 sigma sensitivity the parameter region indicated by the LSND experiment and measure independently the* ν_μ *disappearance with a sensitivity exceeding an order of magnitude the present experimental limits.*
    In the framework of additional sterile neutrinos the ν_e *appearance and* ν_μ *disappearance are mutually related through the relation* $\sin^2 2\vartheta_{e\mu} \sim 0.25 \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$*. Therefore the intrinsic* ν_e *events with a disappearance signal (if confirmed by reactors experiments) may result in the reduction of a superimposed LSND-like* ν_e *signal in the present experiment. These two effects could be disentangled by running with a different intrinsic* ν_e *beam contamination adopting different beam line optics (horn and decay tunnel length).*
    The ability to perform search for oscillation signals in multiple channels is a major advantage for the FNAL SBN oscillation physics program. A simultaneous analysis of ν_e*CC and* ν_μ*CC events will be a very powerful way to explore oscillations and untangle the effects of* $\nu_\mu \rightarrow \nu_e$ *,* $\nu_\mu \rightarrow \nu_x$ *and* $\nu_e \rightarrow \nu_x$ *transitions.*



Sensitivity of the SBN Program (LAr1-ND, MicroBooNE and ICARUS-T600) to νμ→νe (Left) and νμ→νx (Right) oscillation signals. The large event statistics collected by the ICARUS detector in the far position allows to cover at about 5 sigma level the oscillation parameter region indicated by the LSND at 99% CL (Left). The parameter region corresponding to a global fit of all experimental results including the signal anomalies from nuclear reactors and radioactive neutrino sources is also well covered at 5 sigma level. The experiment is exploring the ν_μ disappearance with a sensitivity exceeding an order of magnitude the present MiniBooNE+SciBooNE result (Right).

a. For exclusion limit (such as sterile neutrino search), show 3-sigma and 5-sigma limits: *DONE*.
b. For discovery potential (such as the Mass Hierarchy), show 3-sigma and 5-sigma.
c. For sensitivity plots, show 3-sigma and 5-sigma sensitivities
   (note that for neutrino-less double beta decay experiments that have previously been asked for 90% CL and 5 sigma limits these are OK)
d. List the sources of systematic uncertainties included in the above, their magnitudes and the basis for these estimates:

   Below are listed the systematics evaluated for the full SBN Program in determining the sensitivity to oscillation signals:

   i. *Neutrino flux systematics are evaluated using the BNB Monte Carlo code developed by the MiniBooNE collaboration. Hadron production cross sections and uncertainties are tied to available production data from HARP and other experiments. Primary production, secondary interactions and focusing uncertainties are accounted for. Correlations of the flux between the three detectors have been carefully quantified. After constraint in the near detector, residual flux uncertainties in the far detectors are ~1%.*
   ii. *Cross section systematics and correlations are evaluated using the GENIE neutrino event generator (v2.8). Due to the very high level of correlation between the different detectors and the same target nucleus (argon), the effect of cross section uncertainties on sensitivity cancels out at the first order.*
   iii. *Cosmic background estimates are based on a full FLUKA cosmic flux simulation and propagation into the detector. Cosmogenic background can be significantly reduced by a cosmic muon tagging system, topological cuts and precise timing of the events. The precise event timing will allow also to exploit the bunched structure of the proton beam spill to reject cosmic events. Systematics from residual cosmic backgrounds are small due to the ability to measure the rate precisely in off-beam triggers.*

iv. *"Dirt" background refers to beam-induced out-of-detector interactions that lead to energy deposits in the fiducial volume that can fake signal events (e.g. photons). It has been estimated by extrapolation of a full GENIE+Geant4 simulation in MicroBooNE.*
v. *Detector systematics have been partially evaluated. Relative uncertainties must be kept around 2% or less.*

e. List other experiments that have similar physics goals: *Many experiments are being pursued to search for sterile neutrinos through different approaches including nuclear reactors, mega-curie radioactive sources and meson beams.*
f. Synergies with other experiments: *There is a valuable synergy between the SBN project and pure ν_e disappearance searches with nuclear reactors and radioactive sources. The proposed SBN experiment has the unique advantage of simultaneous measurement in the same experiment of all the neutrino appearance and disappearance channels involved in the sterile neutrino search.*

11. Secondary Physics Goal
    a. Expected results/sensitivity: *ICARUS will make precise measurement of neutrino-argon cross sections with about a million of interactions spanning the few hundreds MeV to few GeV energy range in the Booster Neutrino Beam and with the ν_e enriched off-axis Numi beam. In particular the study of the large sample of ν_e events collected with the off-axis Numi beam will provide valuable information for the future LBNF long baseline neutrino experiment.*
    b. List other experiments that have similar physics goals: *LAr1-ND, MicroBooNE, involved in a common program (SBN) with Icarus, and CAPTAIN-MINERνA.*
12. Experimental requirements
    a. Provide requirements (neutrino source, intensity, running time, location, space,…) for each physics goal:
        i. *Neutrino sources are the Fermilab Booster Neutrino Beam and Numi beam.*
        ii. *The baseline intensity in sensitivity calculations is 2.2e20 pot delivered per year by the Booster and 3e20 pot per year by the Numi beam.*
        iii. *Full SBN sensitivities are shown assuming 6.6e20 pot exposure. Cross sections and other physics measurement can be done with a fraction of the full exposure.*
        iv. *A new detector hall will be constructed at 600 m from target along the Booster Neutrino Beam.*
13. Expected Experiment/Project time line
    a. Design and development: *Dec. 2014-March 2015.*
    b. Construction and Installation: *Jan. 2015-Jan 2017.*
    c. First data: *2017.*
    d. End of data taking: *Early 2020's.*
    e. Final results
14. Estimated cost range
    a. US contribution to the experiment/project: *Funding from US for cryogenics and building, expected total contribution ~$14 M.*
    b. International contribution to the experiment/project: *The existing ICARUS-T600 detector has been developed and constructed in a graded program fully funded by INFN. The overhauling of the detector will be funded by INFN and CERN for a total of ~CHF 13 M (expenses for*

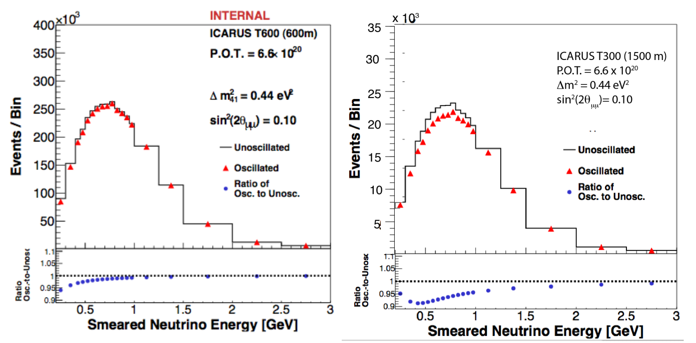
personnel and infrastructures not included) as agreed between INFN and CERN in a MoU signed December 2014.

c. Operations cost: *The sharing of operation costs for the SBN detectors will be defined in due time in a dedicated agreement, shared by all partners.*

15. The Future

a. Possible detector upgrades and their motivation: *The addition of a magnetic field will represent a major improvement to the LAr-TPC technique which will allow for both the particle charge identification and a significant improvement in momentum measurement, opening the possibility to distinguish neutrino from antineutrino interactions.*

b. Potential avenues this project could open up: *If LSND signal is confirmed as true ($\sin^2 2\vartheta_{e\mu}$= 1.5 10^{-3}) and assuming naively muon-electron universality, we expect at FNAL $\sin^2 2\vartheta_{ee}$= $\sin^2 2\vartheta_{\mu\mu} \approx 0.08$, about ½ of the present reactor data and Mega-sources much smaller than claimed. According to the predictions from the Big Bang Cosmology, including the Plank measurements, the mass difference for a sterile neutrino should be small, $\Delta m^2 < 0.4\ eV^2$. In this case the ν_μ disappearance effect in SBN at 600 m will be limited at the lowest neutrino energy bins in the 0.2-0.4 GeV range. Depending on the results of the proposed SBN project, in order to amplify the effect, it is conceivable to move at a later stage one ICARUS T300 module to 1500 m distance.*



Event rate for $\nu\mu \rightarrow \nu x$ disappearance signals for Δm^2=0.44 eV^2 and $\sin^2(2\theta)$ = 0.1 as detected at the SBL far detector located at 600 m (left) and 1500m (right)).

In addition future running in anti-neutrino mode with a magnetized LAr detector could also be envisaged to detect possible CP violating effects. This run could be also used to complete additional physics like antineutrino cross-section measurements.